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NOVEL COLLECTIVE PROTECTION FILTERS FOR EMERGING TIC REQUIREMENTS: AXIAL AND RADIAL-FLOW FILTER DESIGNS

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14. ABSTRACT Adsorbents have recently been developed for enhanced protection against toxic industrial chemicals such as ammonia, ethylene oxide, and nitrogen dioxide. Current collective protection filters employing ASZM-TEDA, an adsorbent developed for heavy organic and acid-forming chemicals, seriously lack protection against these chemicals and other toxic industrial materials. This report explores the development of novel collective protection filters in multiple configurations employing a layered bed of ASZM-TEDA and newly developed zeolites.					
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PREFACE

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NOVEL COLLECTIVE PROTECTION FILTERS FOR EMERGING TIC REQUIREMENTS: AXIAL AND RADIAL-FLOW FILTER DESIGNS

1. OBJECTIVE

The objective of this effort is to design adsorbent beds for novel collective protection filters capable of providing increased protection against toxic industrial chemicals (TICs) compared to current systems. Meeting this objective will require evaluating the ability of novel filtration materials, in conjunction with ASZM-T, to remove target TICs from dry and humid streams of air.

2. BACKGROUND

Current DoD filtration requirements are limited to traditional chemical warfare agents (CWAs) such as GB, HD, and VX as well as acidic/acid-forming gases like cyanogen chloride (CK), hydrogen cyanide (AC) and phosgene (CG). ASZM-T, a bituminous coal-based activated carbon impregnated with salts of copper, silver, zinc and molybdenum as well as triethylenediamine, provides sufficient protection against these compounds to surpass current requirements. ASZM-T is basic in nature and is thus capable of removing many of the acidic TICs. However, because ASZM-T is basic, the filtration material is unable to remove TICs that are basic or base-forming (e.g. ammonia and ethylene oxide). Further, ASZM-T is unable to effectively filter NO_2 and fuming nitric acid. This is because both of these chemicals are reduced to nitric oxide (NO) upon interaction with the surface of ASZM-T, with ASZM-T having no capacity for the removal of NO. Because of the emerging threat associated with TICs, collective protection filters capable of purifying air contaminated with both standard chemical agents and TICs will need to be developed.

In order to develop a collective protection system capable of removing both standard agents and TICs, filtration requirements must first be defined. For this effort, filtration requirements are taken from the Joint Service General Purpose Mask (JSGPM) specification, which includes both traditional chemical agent and TIC filtration requirements. TICs on the ITF-40 list have been grouped such that design-limiting chemicals are utilized to estimate filter performance against the entire list of compounds. A design limiting chemical presents the greatest challenge to the filter within a larger group of similar compounds. Table 1 summarizes the design-limiting chemicals and the corresponding filtration requirements used in designing the collective protection filters.

Table 1. Design-Limiting Chemicals and Corresponding Filtration Requirements.

Chemical	Requirement
Ammonia	42,000 mg-min/m ³
Cyanogen Chloride (CK)	40,000 mg-min/m ³
DMMP	150,000 mg-min/m ³
Ethylene Oxide	Threshold: 40,000 mg-min/m ³ Objective: 108,000 mg-min/m ³
Hydrogen Cyanide (AC)	40,000 mg-min/m ³
Nitrogen Dioxide	Threshold: 5600 mg-min/m ³ Objective: 15,000 mg-min/m ³
Phosgene (CG)	150,000 mg-min/m ³

Table 2 lists filtration materials identified for the removal of standard CW agents and TICs. BF-38-3S consists of acidified zeolite ZSM-5 impregnated with sulfuric acid. BF-38-3S is responsible for filtering basic/base-forming chemicals, such as ammonia and ethylene oxide (Karwacki and Rossin, 2005). KRM-623 consists of impregnated zeolite ZSM-5.* KRM-623 is specifically designed for the filtration of nitrogen dioxide and fuming nitric acid. As Table 2 shows, three different filtration materials are needed in order to provide protection against target CWAs and ITF-40 TICs.

Table 2. Adsorbents Utilized in ColPro Filter Designs.

Adsorbent	Target Chemicals to Filter
ASZM-TEDA	CWA, Acidic/Acid-Forming Gases
BF-38-3S	Basic/Base-Forming Gases
KRM-623	Nitrogen Dioxide

Two collective protection filters are designed in this effort: an axial-flow filter and a radial-flow filter. An axial-flow filter employs an adsorbent bed layered in a linear configuration with the contaminated air stream flowing perpendicularly through the bed. Radial-flow systems utilize a concentric ring-like configuration with the adsorbent bed situated around an annulus or plenum through which the contaminated air stream flows. Different methods are used for designing each of these filters. Figure 1 illustrates the differences between the two filter types.

*Feaver, W.B.; Karwacki, C.J.; Rossin, J.A. Material and Process for the Filtration of Nitric Acid and NO₂ from Streams of Air. U.S. Patent (in process).

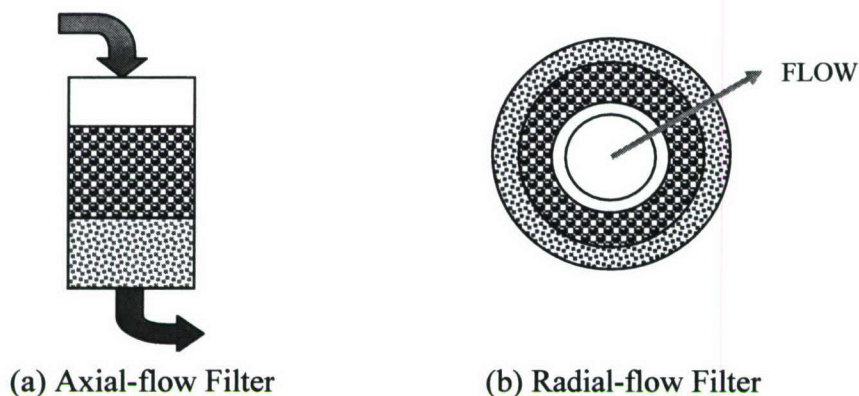


Figure 1. Axial-Flow and Radial-Flow Filter Designs.

In axial filtration systems, the superficial area (the area that the contaminated stream contacts), is constant; therefore, the superficial airflow velocity is constant. As a result, the adsorbents can be layered in test tubes and challenged with the appropriate gases at a constant velocity, which scales to higher flow rates consistent with the operation of the full scale filter. In contrast, radial-flow filters, where the flow enters through the center of the filter, have a constantly increasing superficial surface area as the flow moves from the inside plenum through the adsorbent layers, resulting in a velocity gradient across the adsorbent bed with the maximum airflow velocity at the inlet. Because of the velocity gradient, radial-flow filters employing layered beds must be designed and scaled on a layer-by-layer basis. Design methodology for each filter type is described in detail in Section 3.

3. DISCUSSION

3.1 Axial-Flow Filter Design.

The design of an axial-flow filter capable of meeting the requirements set forth in Table 1 is carried out in several steps. The first step is to determine how each bed is to be layered so that tube test data can be scaled. Figure 2 illustrates the effects of the layered bed filter configuration on the ability of the filter to remove nitrogen dioxide from streams of humid air. If only ASZM-T is employed as the filtration media, or if ASZM-T is located at the filter inlet, nitrogen dioxide will be reduced to NO, with the breakthrough concentration exceeded in approximately 5 min. There is no mechanism for the removal of NO in the current filter configuration. Thus, if NO is formed at the inlet of the filter bed, the NO will rapidly elute through the filter. Placing BF-38-3S at the filter inlet decreases the nitrogen dioxide filtration performance. This performance degradation is attributed to BF-38-3S reducing nitrogen dioxide to NO, which rapidly elutes through the filter bed. KRM-623 is unable to filter NO. Locating a thin layer KRM-623 at the inlet to the filter bed provides as Ct of greater than 15,000 mg-min/m³.

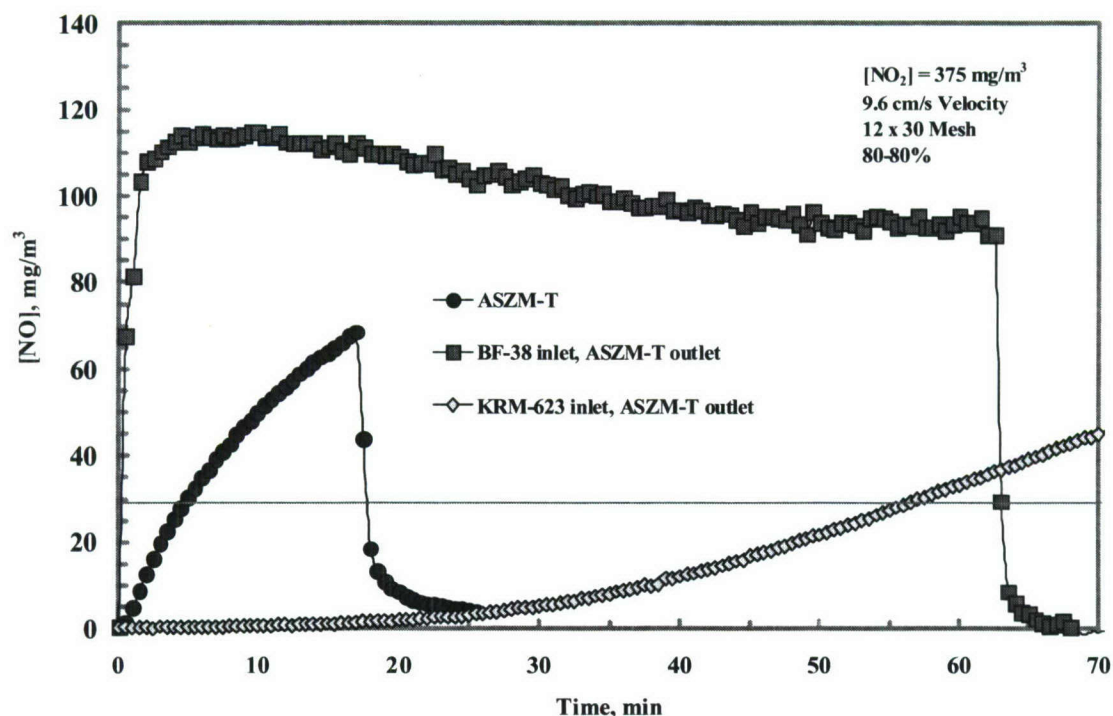


Figure 2. NO₂ Breakthrough Curves Recorded for Selected Filter Bed Configurations.

After the bed configuration is determined, life thickness data are recorded in order to establish the quantity of each adsorbent required to achieve the target level of protection (Table 1). Figure 3 illustrates the effects of the KRM-623 bed depth on the shape and position of the NO breakthrough curves recorded for a nitrogen dioxide challenge of 375 mg/m³. All testing was performed employing a 2.0 cm deep bed of ASZM-T as an outlet layer. It should be noted that it is necessary to include ASZM-T in the filter configuration when recording the filter design data. This is because ASZM-T does contribute to the ability of the filter to remove nitrogen dioxide. Failure to include the ASZM-T will result in a larger than necessary layer of KRM-623 being required.

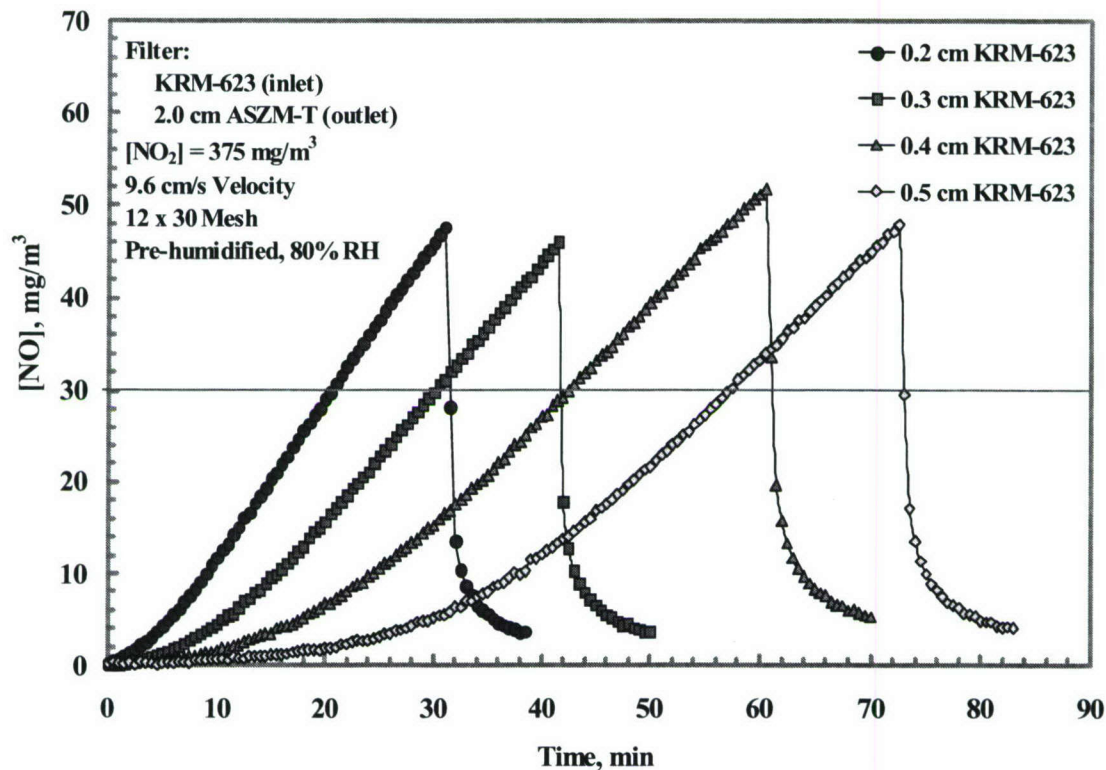


Figure 3. Effects of KRM-623 Bed Depth on NO Breakthrough Curves (NO₂ challenge).

Results presented in Figure 3 were used in determining the necessary KRM-623 bed depth to surpass requirements. Data presented in Figure 3 were correlated as a plot illustrating breakthrough time as a function of the KRM-623 bed depth. These data are presented in Figure 4. The solid lines presented in Figure 4 represent the data correlated using a least squares algorithm. Data follow the expected trend in that a linear relationship is established between the NO breakthrough time and the depth of the KRM-623 filter layer. Nitrogen dioxide filtration results demonstrate that, at an airflow velocity of 9.6 cm/s and a relative humidity of 80% (design limiting relative humidity), a KRM-623 bed depth of at least 0.4 cm is required to surpass the 15,000 mg-min/m³ Ct (40 min) requirement. This bed depth scales to at least a 1.1-cm bed depth at 25.4 cm/s, the airflow velocity of the full-scale collective protection filter, which relates to the superficial area of 2 ft. by 2 ft. at a rated flow of 200 cfm.

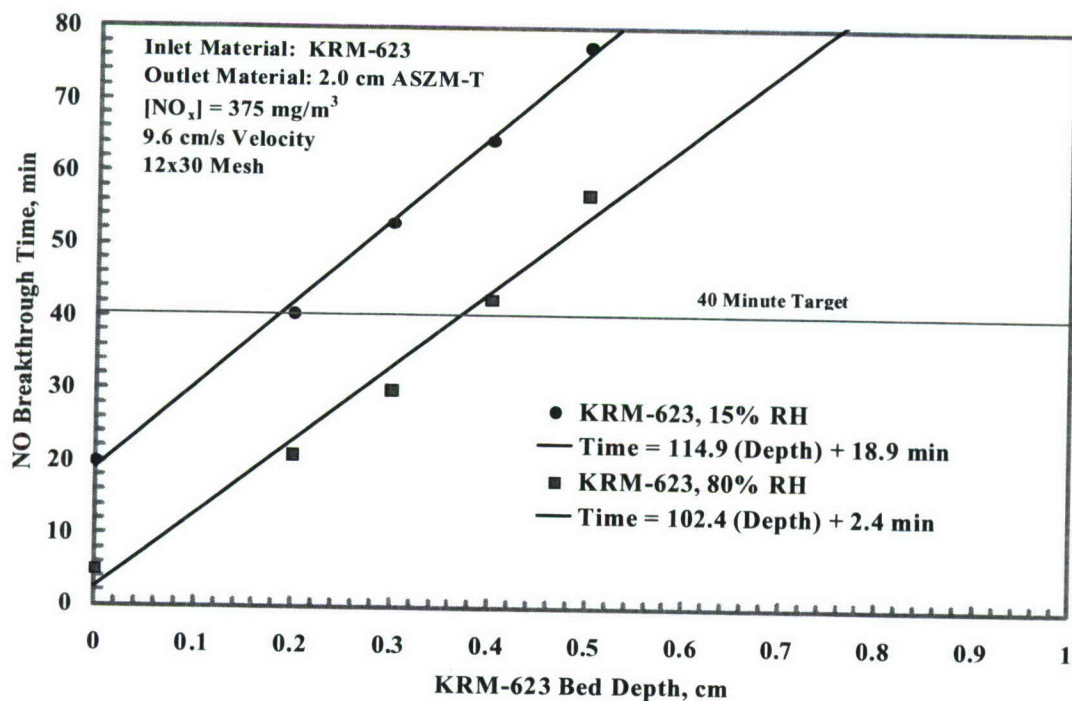


Figure 4. Effects of KRM-623 Bed Depth on NO Breakthrough Time.
 (The target 40-min breakthrough time equates to Ct of 15,000 mg-min/m³.)

The ASZM-T bed depth necessary to surpass requirements is also established using life thickness data. Figure 5 shows cyanogen chloride (CK), hydrogen cyanide (AC) and phosgene filtration dependence on ASZM-T bed depth. Data for CK and AC represent carbon pre-equilibrated at 80% relative humidity and tested at 80% relative humidity. Phosgene data are from testing as-received ASZM-T at 50% relative humidity. From the data collected for the life thickness curves shown in Figure 5, design curves indicate that a bed depth of approximately 4.0 cm is necessary to surpass the hydrogen cyanide requirement, which in this case is the design-limiting acid-forming gas. A bed depth of 4.5 cm will be used so that an appropriate safety margin exists between the performance and the requirement of the filter.

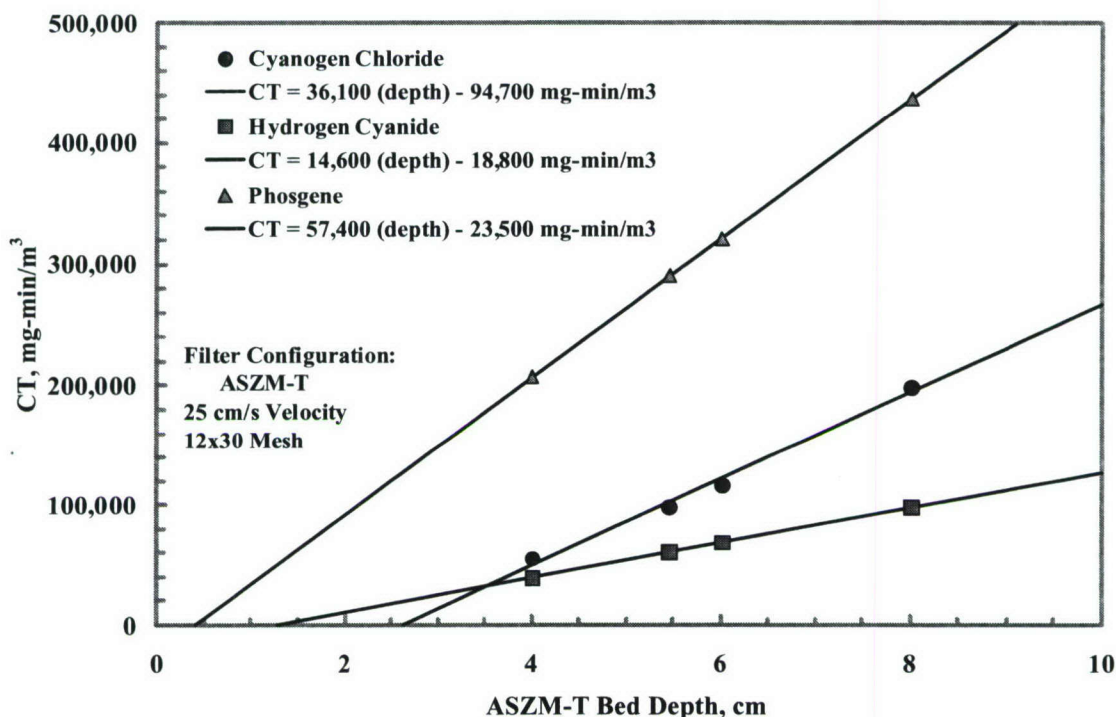


Figure 5. Acid-Forming Gas Filtration Dependence on ASZM-T Bed Depth.*

ASZM-T is also responsible for the filtration of high boiling chemicals (e.g. GB), and the protection afforded by the filter must be established. Using a bed depth of 4.5 cm (equivalent to a residence time of 0.18 s for the 25.4 cm/s airflow velocity), the absolute minimum amount of ASZM-T required to pass acid-forming gas requirements, the DMMP filtration capacity of the filter is determined using eq 1. (DMMP is a simulant used for GB in filter design calculations.)

$$Ct = Ct_{\text{Requirement}} * \left(\frac{RT}{RT_{\text{Requirement}}} \right)^2 \quad (1)$$

where	Ct	= Dosage	[=] mg-min/m ³
	$Ct_{\text{Requirement}}$	= Required Dosage	[=] mg-min/m ³
	RT	= Residence Time	[=] min
	$RT_{\text{Requirement}}$	= Required RT	[=] min

Equation 1 is used to estimate the DMMP filtration performance of minimally acceptable ASZM-T at a residence time other than what the specification calls out. Typically,

*Data from Morrison, R.W.; Karwacki, C.J.; Peterson, G.W. Filtration Performance of the M48A1 Gas-Particulate Filter. Part I: Chemical Warfare Agent Vapors; Guild Associates, Inc., Dublin, OH; US Army Edgewood Chemical Biological Center, Aberdeen Proving Ground, MD, 2004; Unpublished work.

the relationship between dosage and residence time is between a linear and square relationship. In this case, a square correction factor is used as a worst-case estimate, as the residence time used in the filter design is less than that used in the ASZM-T specification. The DMMP minimum requirement for ASZM-T is 175 min at a challenge concentration of $3,000 \text{ mg/m}^3$, or a dosage of $525,000 \text{ mg-min/m}^3$, and the residence time is 0.33 s (2.0-cm bed depth, 6-cm/s airflow velocity). Utilizing eq 1 with said values, the estimated worst-case DMMP filtration capacity of the scaled up filter is equivalent to the requirement of $150,000 \text{ mg-min/m}^3$ due to the lower residence time.

The bed depth of BF-38-3S necessary to provide ammonia and ethylene oxide protection such that the requirements in Table 1 are satisfied is also established using life thickness data. Ethylene oxide life thickness data are shown in Figure 6 which shows that increasing the amount of BF-38-3S just a few millimeters greatly improves ethylene oxide filtration. Ammonia life thickness data are also necessary in order to determine which chemical is design-limiting for BF-38-3S. The ammonia filtration performance as a function of BF-38-3S bed depth is shown in Figure 7.

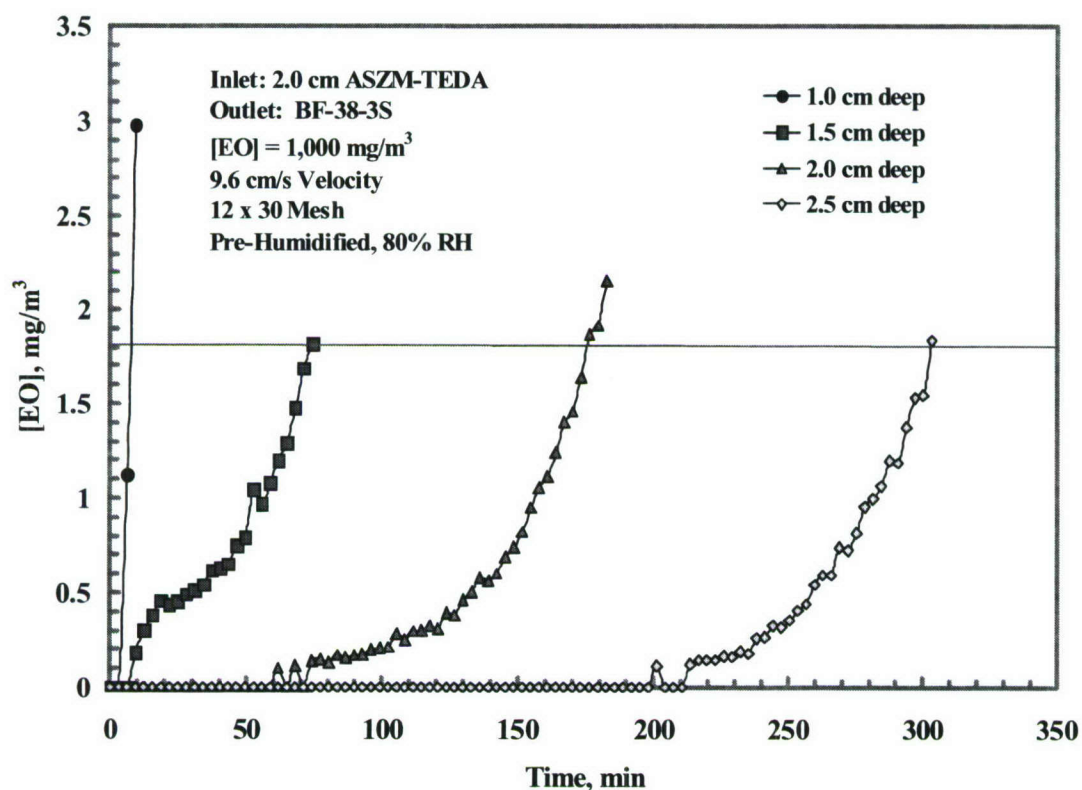


Figure 6. Ethylene Oxide Breakthrough Curves as a Function of BF-38-3S Bed Depth.

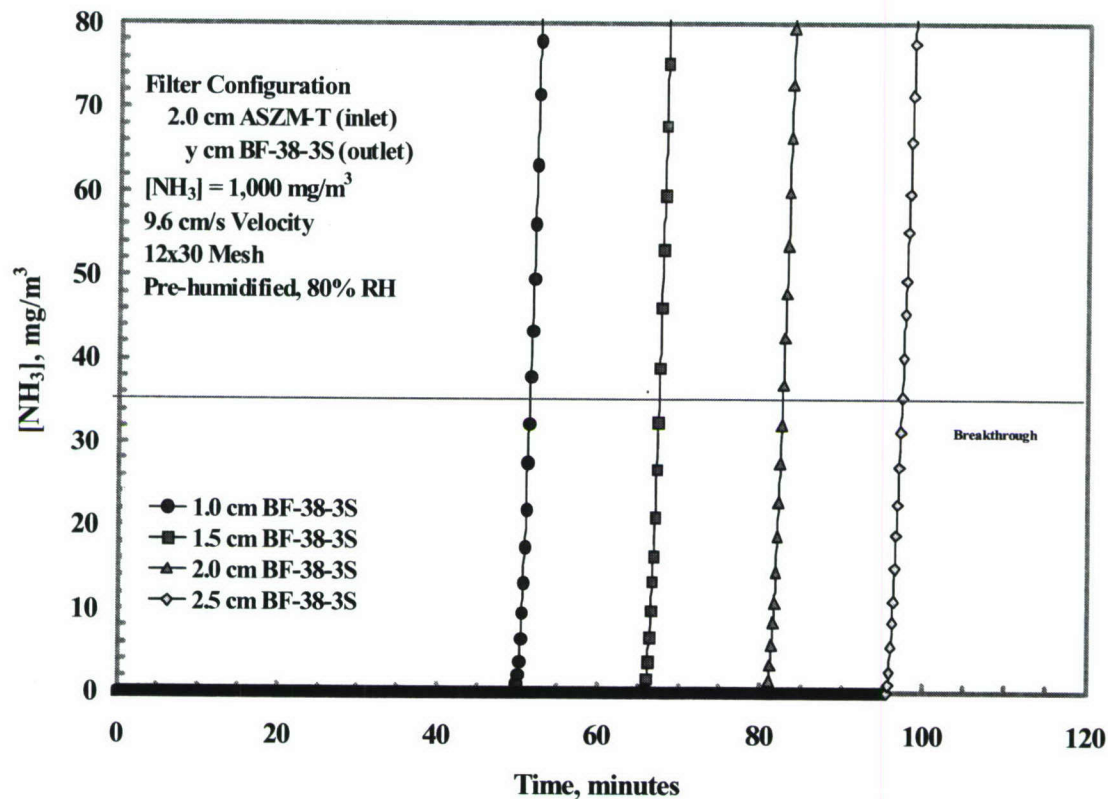


Figure 7. Ammonia Breakthrough Curves as a Function of BF-38-3S Bed Depth.

As Figure 7 illustrates, ammonia is also effectively filtered by BF-38-3S. Ammonia and ethylene oxide breakthrough times are correlated as a function of the BF-38-3S bed depth. It should be noted that all data were recorded using a filtration bed consisting of 2.0 cm ASZM-T (inlet) over varying layers of BF-38-3S (outlet). In the case of ethylene oxide, ASZM-T has virtually no capacity under humid test conditions. In the case of NH_3 , ASZM-T has minimal capacity for the removal under dry test conditions, and some capacity for the removal of NH_3 under humid test conditions.

Figure 8 illustrates filter design curves relating the NH_3 and EO breakthrough times as a function of the BF-38-3S bed depth. As Figure 8 shows, ammonia breakthrough under both dry and humid conditions is nearly identical and requires approximately 0.6 to 0.8 cm of BF-38-3S to meet the proposed requirements. The quantity of BF-38-3S necessary to surpass the ethylene oxide requirement is approximately twice as much at 1.2 cm. Scaling this bed depth to the higher velocity results in a BF-38-3S bed depth of approximately 3.2 cm. Several millimeters must be added to establish an appropriate safety margin.

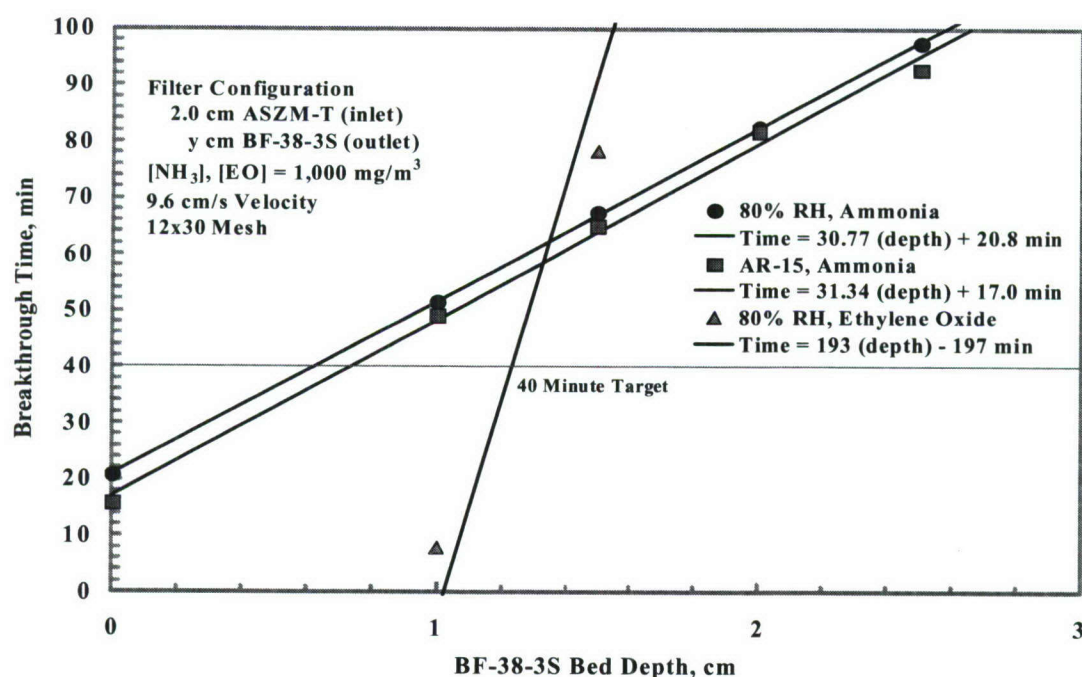


Figure 8. NH_3 and EO Breakthrough Times of BF-38-3S.

Design data has been collected for the various design-limiting chemicals on the three adsorbents of the proposed filter. Table 3 summarizes the bed depths and configuration of the proposed axial-flow collective protection filter.

Table 3. Proposed Axial-Flow Filter Configuration.

Adsorbent	Layer	Bed Depth
KRM-623	Inlet	1.3 cm
ASZM-TEDA	Middle	4.5 cm
BF-38-3S	Exit	3.9 cm

As discussed earlier, axial-flow filters can be tested in tubes and then scaled to accommodate higher flow rates. The proposed filter was tested against the design-limiting chemicals in order to identify any shortcomings. Results are summarized in Table 4.

Table 4. Axial-Flow Filter Performance against Design-Limiting Chemicals
@ 1,000 mg/m³ Challenge, 25.4 cm/s AFV and 80 °F.

Chemical	Performance @ AR/15% RH	Performance @ 80/80% RH
Ammonia	60,000 mg-min/m ³	59,000 mg-min/m ³
Cyanogen Chloride (CK)	TBD	>70,000 mg-min/m ³ *
DMMP	>150,000 mg-min/m ³ *	n/a
Ethylene Oxide	193,000 mg-min/m ³	107,000 mg-min/m ³
Hydrogen Cyanide (AC)	TBD	>50,000 mg-min/m ³ *
Nitrogen Dioxide	22,000 mg-min/m ³	35,000 mg-min/m ³
Phosgene (CG)	344,000 mg-min/m ³	>344,000 mg-min/m ³

*Determined from residence time correlations

Breakthrough data presented in Table 4 show that the proposed axial-flow filter surpasses all threshold requirements for each design-limiting chemical, with some results indicating that the filter may be over-designed. For instance, in order to meet threshold requirements (Table 1), all three layers provide a large margin for safety. In regards to objective requirements, the BF-38-3S layer would have to grow a small amount in order to increase ethylene oxide filtration performance.

3.2 Radial-Flow Filter Design.

Recent developments have shown the capability to decrease the HEPA footprint in radial-flow filters, allowing for an increased adsorbent bed depth for the same outer space claim. Specifically, the M98 filter set was studied for the possibility of utilizing the same outer shell for the novel adsorbent bed so that individual filters could be changed out without modifying the entire collective protection system.

Design data for the radial-flow filter were collected differently than data for the axial-flow filter. Because radial-flow filters have a velocity gradient, the residence time used to scale the adsorbent bed on a layer-by-layer basis. Residence time can be mathematically defined as either the bed depth divided by the airflow velocity or the adsorbent volume divided by the flow rate, which is independent of the velocity gradient. Therefore, data were collected on a layer-by-layer basis for the radial-flow filter design utilizing the appropriate log-mean airflow velocities during tube testing. Furthermore, because testing was conducted on a layer-by-layer basis, synergistic effects between layers, which may help attenuate the wavefront through the bed, are not taken into account in the design phase, thus representing a worst-case scenario.

The methodology used in designing the radial-flow filters varies from the axial-flow method. The radial-flow filter has a limited space claim defined by the inner plenum and the outer shell of the filter, and therefore bed depths for each adsorbent must be optimized in order to design the overall bed that comes closest to meeting the proposed requirements. This is an iterative process, as the bed depth of each layer must be changed several times in order to get the optimum overall performance of the filter. From the axial-flow filter design, the bed configuration has already been determined: KRM-623 must be the inlet layer to provide

protection against nitrogen dioxide, ASZM-T is the middle layer to provide additional nitrogen dioxide protection, and BF-38-3S is the outlet layer. This configuration also protects BF-38-3S from being poisoned due to ambient organics and contaminants as the heterogeneous pore structure of ASZM-T adsorbs these chemicals.

The first step in the radial-flow filter design is to assume a KRM-623 bed depth capable of meeting the nitrogen dioxide requirements. From the assumed bed depth, the inside and outside surface area is calculated from eqs 2-4.

$$SA_{Inside} = 2\pi * \frac{ID}{2} * h \quad (2)$$

$$SA_{Outside} = 2\pi * \frac{OD}{2} * h \quad (3)$$

$$\text{with } OD = ID + 2 * BD \quad (4)$$

where	SA_{Inside}	= Inside surface area of adsorbent layer	[=] cm^2
	$SA_{Outside}$	= Outside surface area of adsorbent layer	[=] cm^2
	ID	= Inside diameter of adsorbent layer	[=] cm
	OD	= Outside diameter of adsorbent layer	[=] cm
	h	= Adsorbent layer height	[=] cm
	BD	= Adsorbent layer bed depth	[=] cm

Once the inside and outside surface areas are calculated, the airflow velocity at the inlet and outlet of the layer is calculated from eqs 5 and 6.

$$AFV_{Inlet} = \frac{FlowRate}{SA_{Inside}} \quad (5)$$

$$AFV_{Outlet} = \frac{FlowRate}{SA_{Outlet}} \quad (6)$$

where	AFV_{Inlet}	= Airflow velocity at adsorbent layer inlet	[=] cm/s
	AFV_{Outlet}	= Airflow velocity at adsorbent layer outlet	[=] cm/s
	Flow Rate	= Airflow rate	[=] cm^3/s

The log-mean airflow velocity is calculated using a geometric mean of the inlet and outlet airflow velocities, as shown in eq 7.

$$\Delta_{LM} AFV = \frac{AFV_{Inlet} - AFV_{Outlet}}{\ln\left(\frac{AFV_{Inlet}}{AFV_{Outlet}}\right)} \quad (7)$$

From the calculated log-mean airflow velocity, the residence time of the KRM-623 layer is established using the assumed bed depth, as shown in eq 8. Equation 9 shows an alternative to calculating the residence time utilizing the flow rate and volume of the adsorbent layer.

$$RT = \frac{BD}{\Delta_{LM} AFV} \quad (8)$$

$$RT = \frac{Volume_{Adsorbent}}{FlowRate} \quad (9)$$

where RT = Residence time [=] s

A residence time has been established for the KRM-623 layer, and therefore the nitrogen dioxide filtration performance can be estimated using residence time correlations shown in Figure 9.

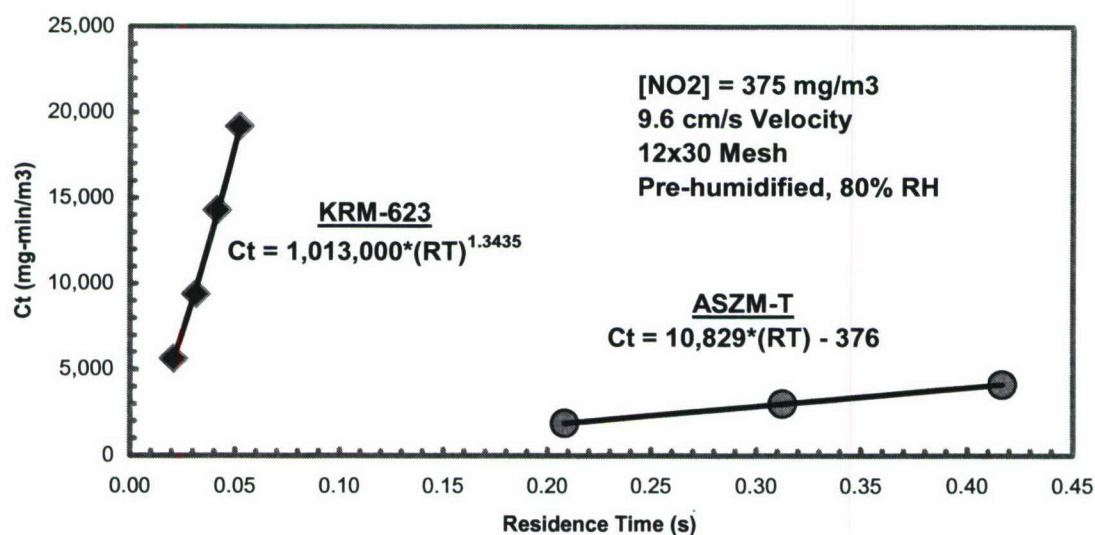


Figure 9. NO₂ Design Data for Radial-Flow Filter.

As shown in Figure 9, both KRM-623 and ASZM-T have filtration capabilities against nitrogen dioxide; however, KRM-623 provides much better protection at much lower residence times.

As the bed depth of KRM-623 has been established, the process is repeated for ASZM-T. Similar to the estimation of the KRM-623 filtration performance, a bed depth of ASZM-T is assumed that will meet requirements for both strongly adsorbed chemicals as well as acidic/acid-forming gases. For acidic/acid-forming gases of concern, Figure 5 was re-plotted to

correlate filtration performance as a function of residence time. These data are illustrated in Figure 10.

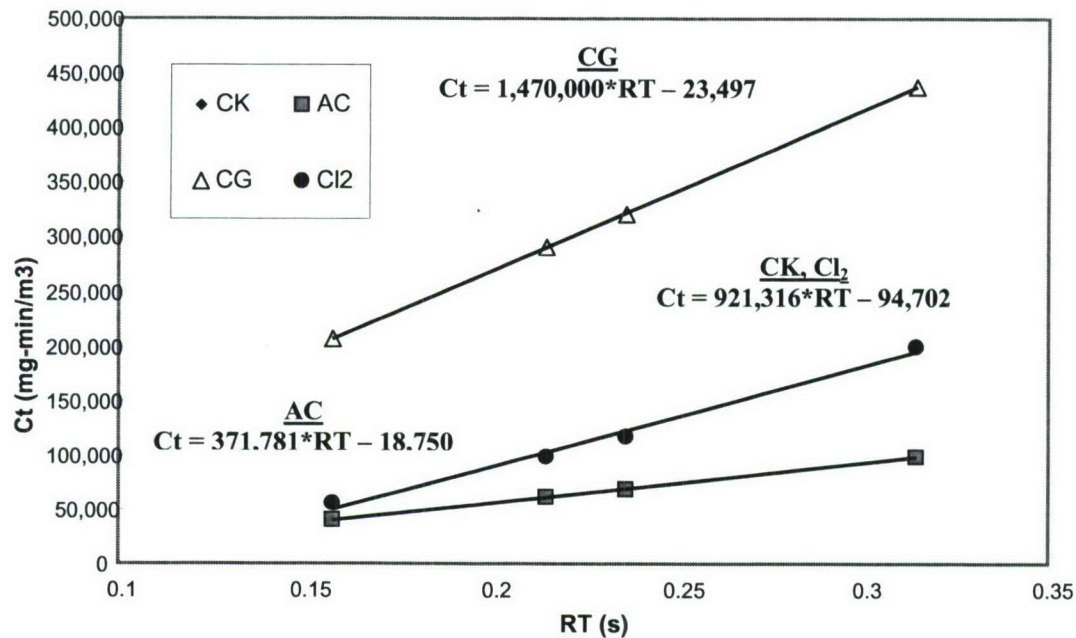


Figure 10. Acid-Gas Filtration Performance as a Function of Residence Time on ASZM-T.

As with the axial-flow filter, the DMMP performance was estimated utilizing eq 1, establishing the performance of the ASZM-T layer.

Because bed depths have been assumed for both the KRM-623 and ASZM-T layers, the BF-38-3S layer bed depth is now known due to the fixed outer diameter of the adsorbent bed of the filter. Utilizing residence time correlations shown in Figure 11 for ammonia and ethylene oxide filtration performance of BF-38-3S, the protection afforded by this layer is ascertained.

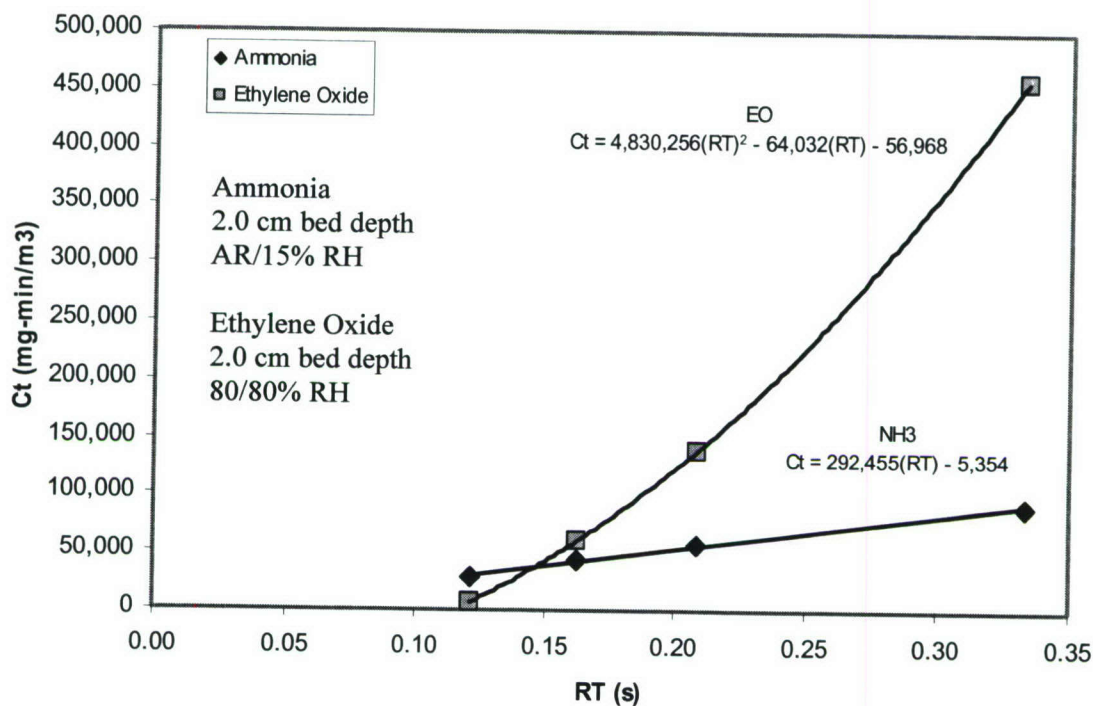


Figure 11. BF-38-3S Radial-Flow Filter Design Data.

Once the protection of the entire adsorbent bed has been determined, the iteration must be re-started in order to determine the optimum protection pertaining to all chemicals. After several iterations, the following parameters were established for the radial-flow filter (Table 5).

Table 5. Filter Parameters for the Novel Radial-Flow Filter.

Adsorbent Layer	Bed Depth	Log-mean Airflow Velocity	Residence Time
KRM-623 (inlet)	1.5 cm	36.3 cm/s	0.041 s
ASZM-T (middle)	5.2 cm	30.6 cm/s	0.170 s
BF-38-3S (exit)	4.3 cm	24.6 cm/s	0.175 s
Overall Bed	11.0 cm	29.6 cm/s	0.386 s

From the residence time correlations described in this section, the filtration performance estimations in Table 6 were determined. CK, AC, ethylene oxide, and nitrogen dioxide estimations are all at 80/80% relative humidity while ammonia, DMMP and CG estimations are at AR/15% relative humidity. In this manner, filtration performance under design-limiting conditions for target chemicals is established.

Table 6. Filtration Performance of the Novel Radial-Flow Filter.

Chemical	Objective Requirement	Estimated Filtration Performance
Ammonia	42,000 mg-min/m ³	48,100 mg-min/m ³
Cyanogen chloride (CK)	40,000 mg-min/m ³	61,900 mg-min/m ³
DMMP	150,000 mg-min/m ³	214,950 mg-min/m ³
Ethylene oxide	108,000 mg-min/m ³	111,700 mg-min/m ³
Hydrogen cyanide (AC)	40,000 mg-min/m ³	44,500 mg-min/m ³
Nitrogen dioxide	15,000 mg-min/m ³	15,500 mg-min/m ³
Phosgene (CG)	150,000 mg-min/m ³	226,400 mg-min/m ³

The estimations in Table 6 show that, like the proposed axial-flow filter, all requirements are met; however, unlike the proposed axial-flow filter, there is much less of a safety margin in performance over the requirement for almost all of the chemicals due to the lack of available space in the filter.

4. CONCLUSIONS AND RECOMMENDATIONS

Two different collective protection filters are proposed that incorporate filtration capabilities against both chemical warfare agents (CWAs) and toxic industrial chemicals (TICs). Each filter includes a layered bed configuration consisting of KRM-623, a nitrogen dioxide sorbent, ASZM-T, a sorbent used in the filtration of CWAs and acid gases, and BF-38-3S, a zeolite used in the filtration of basic gases. Both filters surpass requirements taken from the Joint Service General Purpose Mask (JSGPM) program.

The proposed axial-flow filter is rated at 200 cfm with a superficial area of two by two feet and a total adsorbent bed depth of 9.7 cm. The filter passes threshold requirements with a large safety margin, but must grow slightly in the BF-38-3S layer in order to pass ethylene oxide objective requirements.

The proposed radial-flow filter is also rated at 200 cfm and has a total adsorbent bed depth of 11.0 cm. The radial-flow bed depth must be larger than the axial-flow bed depth due to the increased airflow velocities seen in the inner adsorbent bed volume in the radial-flow filter. The radial-flow filter passes all objective requirements, but with little safety margin. The radial-flow filter also is dependent on a much smaller HEPA footprint than those currently used in practice, which of yet is an unproven technology.

The proposed filters both provide extensive protection against CWAs and TICs; however, the power requirements for each filter have yet to be investigated. In order to characterize the power requirements of the proposed filters and compare them to currently fielded systems, the airflow resistance of each must be measured followed by a trade study of protection versus power.

Both the axial and radial-flow filters must also be evaluated for their tendency to age; included in these studies would be accelerated aging in both a high relative humidity environment and a high temperature environment. These experiments will characterize the tendency of ASZM-T to off-gas both triethylenediamine (TEDA) and ammonia and quantify any potential poisoning effects on the BF-38-3S layer.

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APPENDIX

SAMPLE ITERATION FOR RADIAL-FLOW FILTER DESIGN

1. Adsorbent Bed Dimension

- Bed Height = 9.63" = 24.47 cm
- Inside Diameter = 12.75" = 32.39 cm
 - Assumed from HEPA outside diameter
- Outside Diameter = 21.41" = 54.39 cm

2. Inside Superficial Area

$$SA_{Inside} = 2\pi * \frac{ID}{2} * h$$

where SA_{Inside} = Inside superficial area [=] cm²
ID = Inside diameter [=] cm
h = Adsorbent bed height [=] cm

ITERATION

3. Assume KRM-623 Bed Depth

4. Outside Superficial Area

$$SA_{Outside} = 2\pi * \frac{OD}{2} * h$$

$$OD = ID + 2 * BD$$

where $SA_{Outside}$ = Outside superficial area [=] cm²
OD = Outside diameter [=] cm
h = Adsorbent bed height [=] cm
BD = Bed depth [=] cm

5. Inside & Outside Airflow Velocity

$$AFV_{Inlet} = \frac{FR}{SA_{Inside}}$$

where AFV_{Inlet} = Inlet airflow velocity to adsorbent bed [=] cm/s
 FR = Flow Rate [=] cm³/s
 SA_{Inside} = Inside superficial area [=] cm²

$$AFV_{Outlet} = \frac{FR}{SA_{Outside}}$$

where AFV_{Outlet} = Outlet airflow velocity to adsorbent bed [=] cm/s
 FR = Flow Rate [=] cm³/s
 $SA_{Outside}$ = Outside superficial area [=] cm²

6. Log-Mean Airflow Velocity

$$\Delta_{LM} AFV = \frac{AFV_{Inlet} - AFV_{Outlet}}{\ln\left(\frac{AFV_{Inlet}}{AFV_{Outlet}}\right)}$$

where $\Delta_{LM} AFV$ = Log-mean airflow velocity [=] cm/s
 AFV_{Inlet} = Inlet airflow velocity to adsorbent bed [=] cm/s
 AFV_{Outlet} = Outlet airflow velocity to adsorbent bed [=] cm/s

7. Residence Time

$$RT = \frac{BD}{\Delta_{LM} AFV}$$

OR

$$RT = \frac{V}{FR}$$

where RT = Residence time [=] s
 BD = Bed depth [=] cm
 $\Delta_{LM} AFV$ = Log-mean airflow velocity [=] cm/s
 V = Adsorbent volume [=] cm³
 FR = Flow rate [=] cm³/s

8. RT Correlations

- Collect data of filtration performance vs. residence time for KRM-623
- Repeat iteration until filtration performance exceeds requirement

END ITERATION

9. Repeat iteration for ASZM-TEDA until CWA, acid gas requirements met

- Inside diameter of ASZM-TEDA = Outside diameter of KRM-623

10. Remaining adsorbent bed depth is BF-38

- Inside diameter of BF-38 = Outside diameter of ASZM-TEDA
- Outside diameter of BF-38 is fixed @

ITERATION

11. Optimize Bed Depths

- Determine optimum bed depth for each adsorbent layer to give the best overall filtration performance.